The MICROSCOPE space mission to test the Equivalence Principle

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on behalf the MICRSCOPE Team

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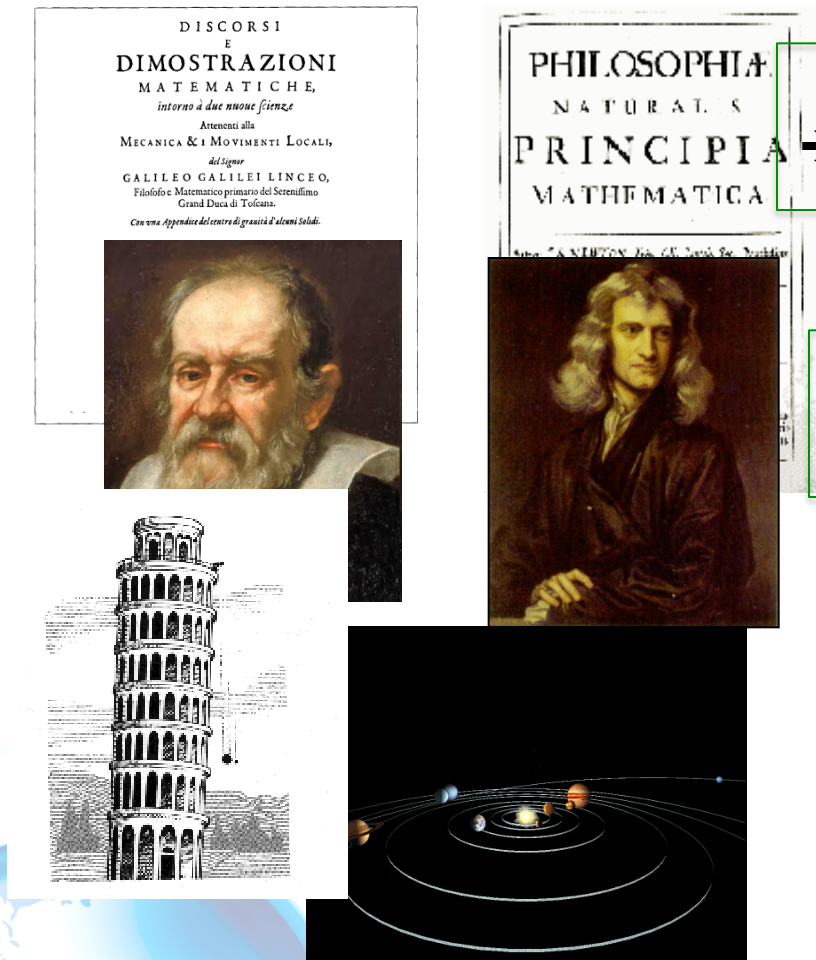
Newton : Gravitational mass and Inertial mass



Gravitational law
➔ Gravitational mass

$$F_G = -\frac{G m_G^1 \, m_G^2}{r^2}$$

➕

Dynamical law
➔ Inertial mass

$$F = m_I a \quad \Rightarrow \quad m_I = \frac{F}{a}$$

Free fall motion
➔ Ratio of the 2 masses

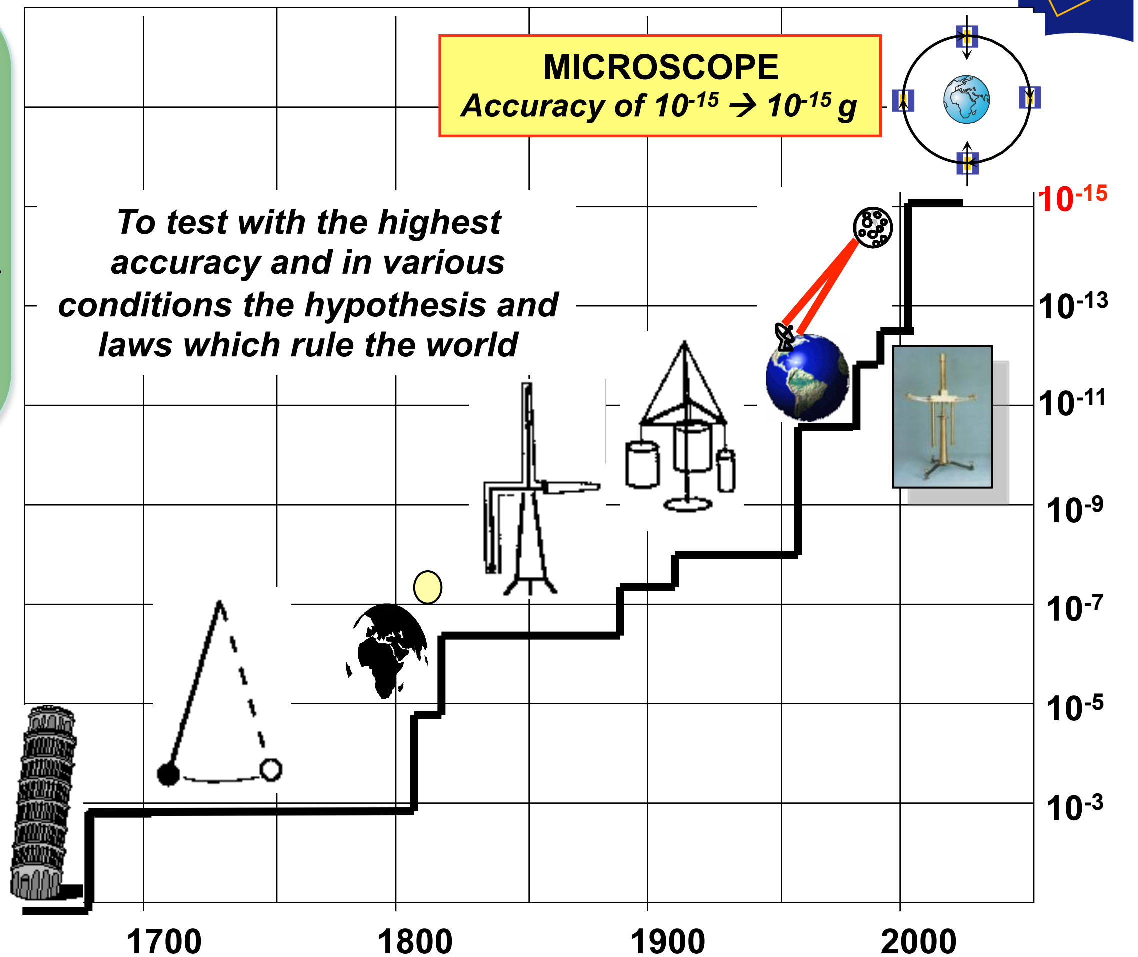
$$\Rightarrow a_G = -\frac{G m_G^2}{r^2} \frac{m_G^1}{m_I^1} = -g \frac{m_G^1}{m_I^1}$$

The Universality of Free Fall

Eotvos parameter:

$$\eta_{12} = 2\frac{\dfrac{m_{g1}}{m_{i1}} - \dfrac{m_{g2}}{m_{i2}}}{\dfrac{m_{g1}}{m_{i1}} + \dfrac{m_{g2}}{m_{i2}}} \approx \frac{m_{g1}}{m_{i1}} - \frac{m_{g2}}{m_{i2}}$$

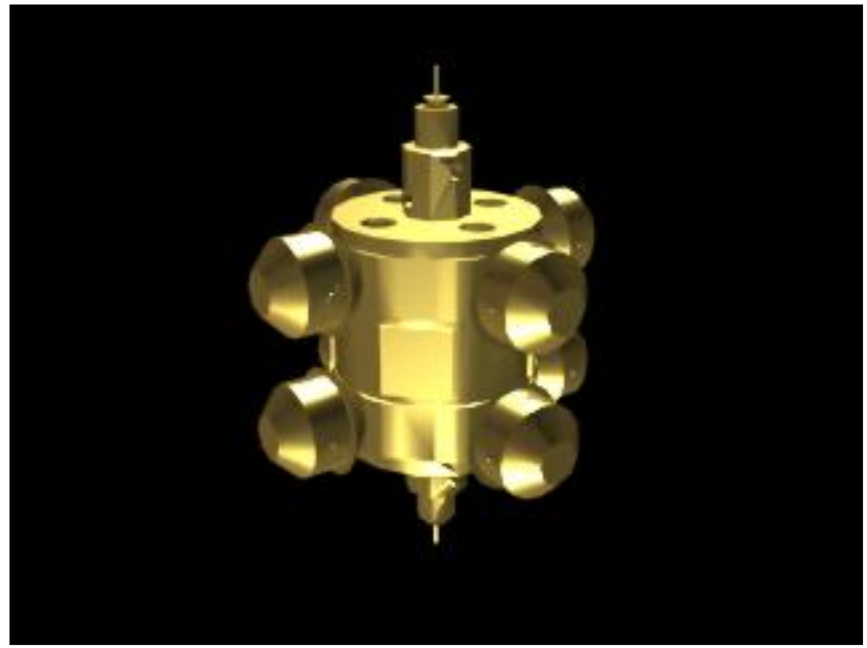
Experiments ➔
$\eta < 10^{-13}$
for various materials



MICROSCOPE space experiment: test of the Equivalence Principle with an accuracy of 10^{-15}

The Eot-Wash experiment

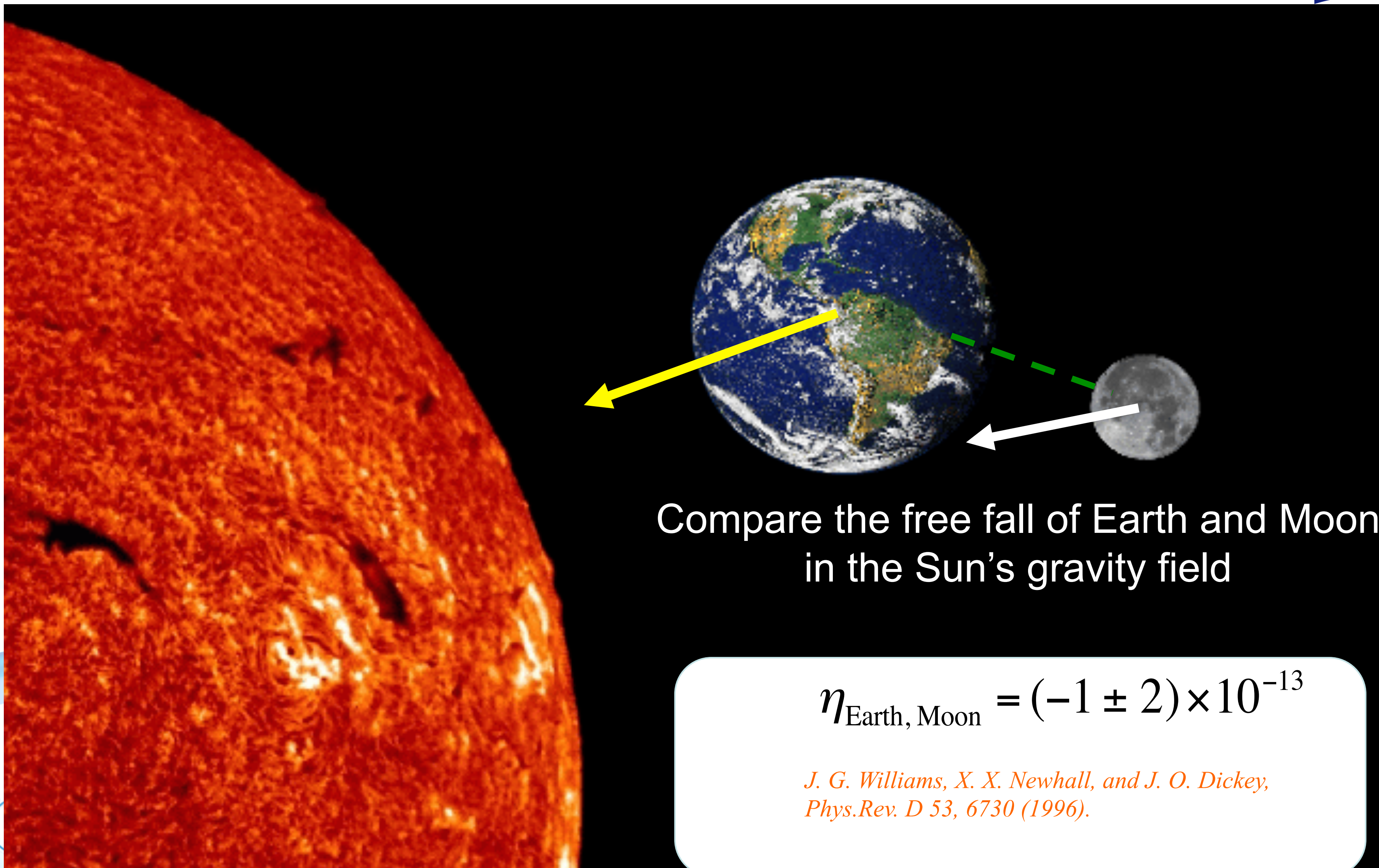
A torsion balance in rotation to compare the UFF of various materials



$$\eta(Earth, Be - Ti) = (0.3 \pm 1.8).10^{-13}$$

Schlamminger, S. et al. Test of the Equivalence Principle Using a Rotating Torsion Balance". Physical Review Letters 100, 4, (2008).

Lunar Laser Ranging

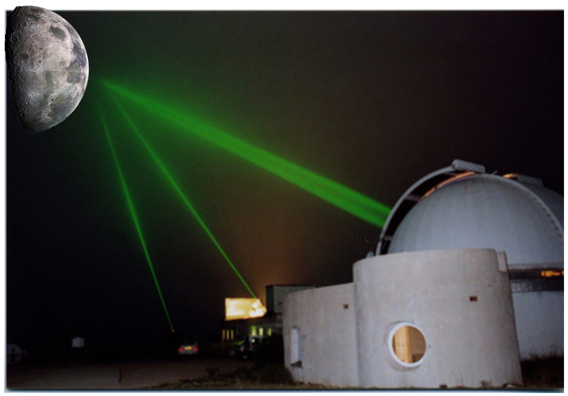


Compare the free fall of Earth and Moon in the Sun's gravity field

$$\eta_{\text{Earth, Moon}} = (-1 \pm 2) \times 10^{-13}$$

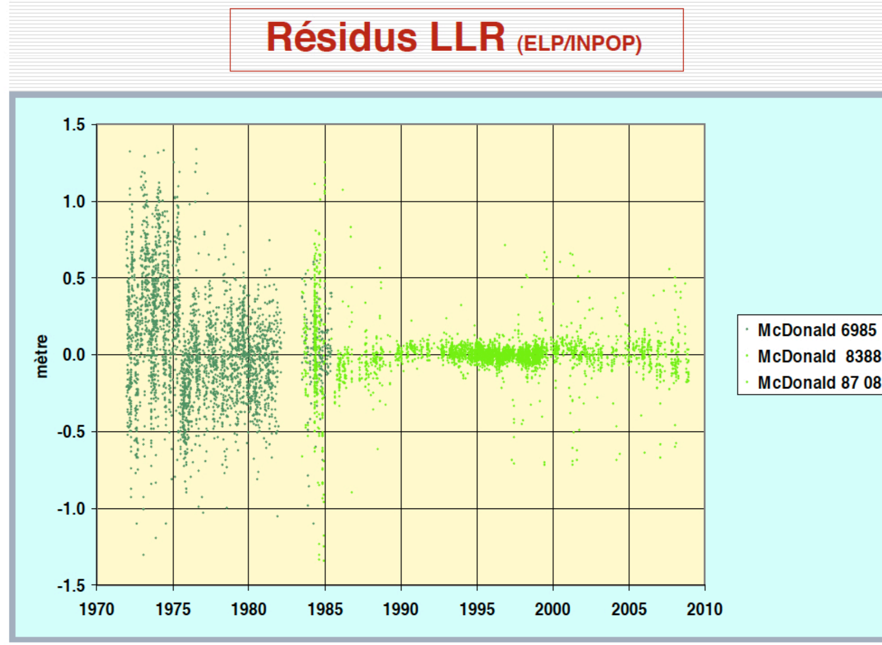
J. G. Williams, X. X. Newhall, and J. O. Dickey, Phys.Rev. D 53, 6730 (1996).

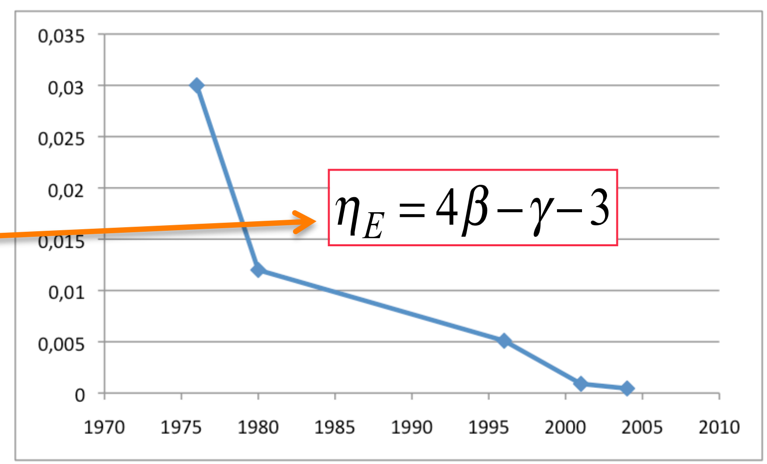
Télémétrie laser sur la Lune et le principe d'équivalence



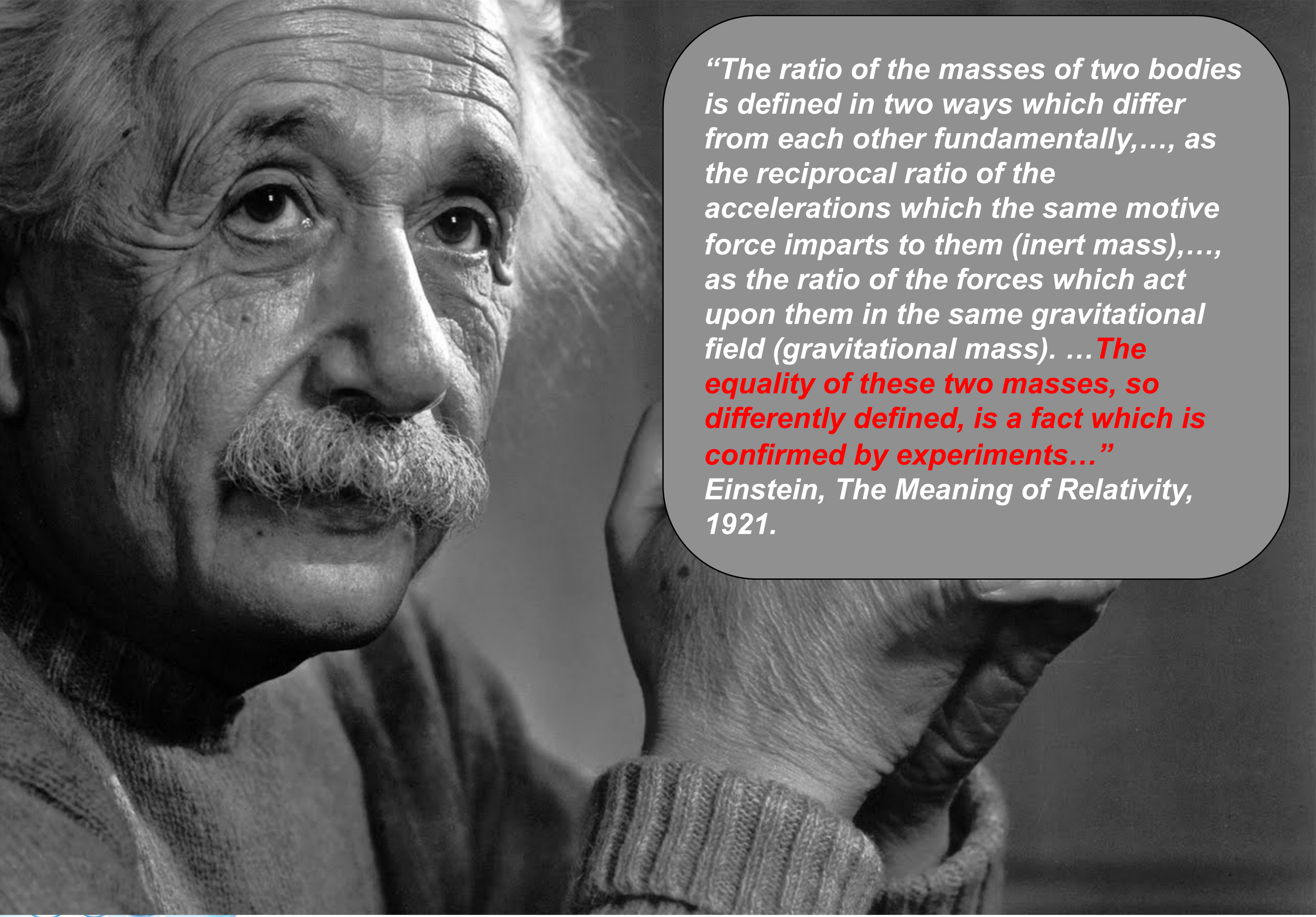
MeO: télémétrie laser sur satellites et sur la Lune (plateau de Calern)

$$\eta = \left[\frac{M_G}{M_I}\right]_E - \left[\frac{M_G}{M_I}\right]_M = (-1 \pm 2)\times 10^{-13}$$





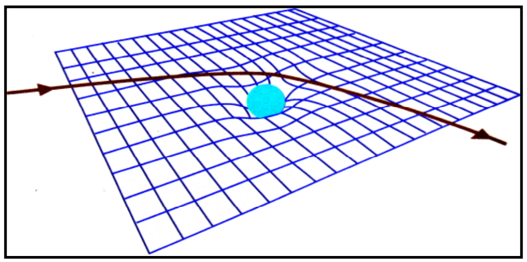
$$\eta_E = 4\beta - \gamma - 3$$

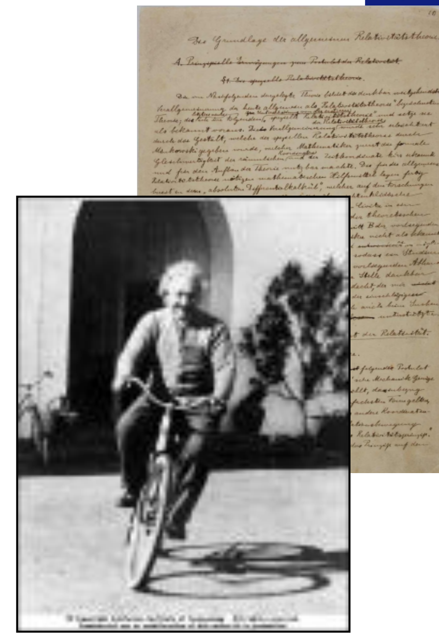


“The ratio of the masses of two bodies is defined in two ways which differ from each other fundamentally,…, as the reciprocal ratio of the accelerations which the same motive force imparts to them (inert mass),…, as the ratio of the forces which act upon them in the same gravitational field (gravitational mass). …The equality of these two masses, so differently defined, is a fact which is confirmed by experiments…”
Einstein, The Meaning of Relativity, 1921.

Einstein : General Relativity

Gravity is the result of the curvature of space-time :





$$T_{\mu\nu} = \frac{8\pi G}{c^4} \cdot G_{\mu\nu}$$

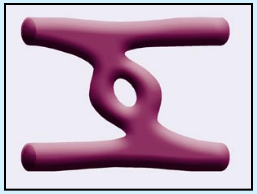
$$T_{\mu\nu} \Rightarrow g_{\mu\nu}$$

General Relativity
Space Time metric
& geodesic free motion
Eddington 1919, Gravitational deflection of light
Mercury perihelion precession
1916.

MICROSCOPE RATIONALE

Two formalisms

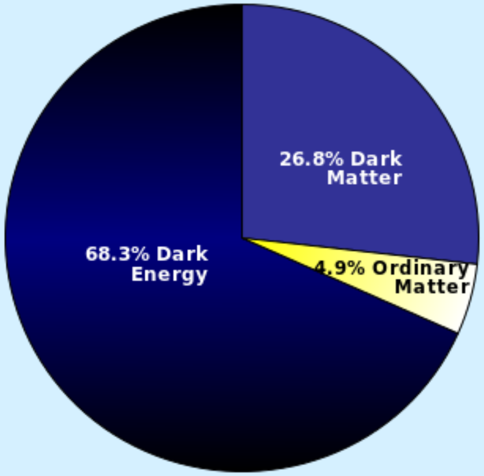
- **Small scales described by quantum field theory**



- **Large scale described by General Relativity**
  - **geometrical theory, not (yet?) a quantum field theory**

Under development :

- **String, Brane theories**
- **Loop Quantum Gravity**



ESA roadmap for fundamental physics in space, 2010.

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47598

→ **Tests of fundamental laws and principles**

→ **Search for fundamental constituents**

Extract from EP test colloquium (Palaiseau, 19 Sept. 2011) :
Thibault Damour presentation conclusions

Conclusions (II)

- $\exists$ no firm prediction for level of EP violation, but some phenomenological models show that the violation could naturally be just below the currently tested level.

- In dilaton-like models, the composition-dependence of EP signals is (probably) dominated by two signals, depending on $A^{-1/3}$ and $Z^2\,A^{-4/3}$.

- In such dilaton-like models, there exist correlated modifications of gravity ($\Delta a/a$, $\gamma^{\rm PPN}-1 \neq 0$, $\dot{\alpha}_a \neq 0$, $d\alpha_a/dU \neq 0, \ldots$) but EP tests stand out as our deepest probe of new physics, when compared to, e.g., solar-system ($\gamma^{\rm PPN}$) or clock tests ($\dot{\alpha}_a$ or $d\alpha_a/dU$). Indeed,

$$\frac{\Delta a}{a} \sim 10^{-2}\,\frac{d_q}{d_g}\,\frac{1-\gamma^{\rm PPN}}{2}$$

where $d_q \equiv \partial\,\ell n(m_q/\Lambda_{\rm QCD})/\partial\varphi$, $d_g \equiv \partial\,\ell n(\Lambda_{\rm QCD}/m_{\rm Planck})/\partial\varphi$ and either $d_q \sim d_g$ or $d_q \sim d_g/40$. In the "worst case" $1-\gamma^{\rm PPN} \sim 10^4\,\Delta a/a$ so that $\Delta a/a \sim 10^{-15} \rightarrow 1-\gamma^{\rm PPN} \sim 10^{-11}$.

Thibault Damour (IHES) — Testing the Equivalence Principle — ONERA — 19/09/2011 — 14 / 14

T Damour et al., PRL vol.89, Nr.8, 2002 : «Our results suggest that the residual dilaton couplings today...corresponding to a violation of the UFF at the $\Delta a/a \sim 10^{-12}$ »

Objectif de Microscope

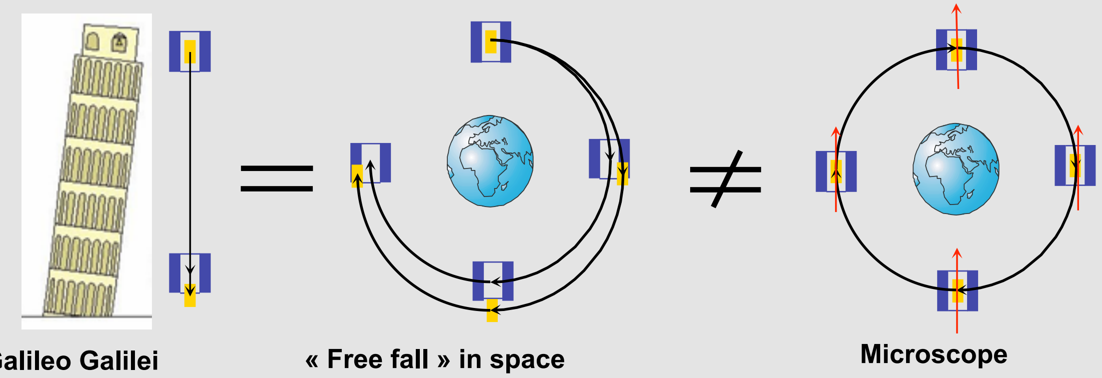
- Tester l'identité de la chute libre de deux masses de composition chimique différentes avec une précision et exactitude meilleure que 10^{-15}
- Choix des matériaux : compromis entre l'intérêt scientifique, la réalisation technologique (usinage des masses d'épreuve…) et la précision instrumentale (susceptibilité magnétique, dilatation thermique,…)
- Damour-Donoghue, 2010 : $\eta \propto \frac{c_1}{A^{1/3}} + c_2 \frac{Z^2}{A^{4/3}}$
- Microscope : Titane (A=48,Z=22) et Platine (A=195,Z=18)

Cela veut dire quoi 10^{-15} ?

$$\Delta\left(\frac{m_g}{m_i}\right) = 10^{-15} \Rightarrow \Delta\gamma = 10^{-15} g \sim 8\ 10^{-15}\ \mathrm{ms}^{-2}$$

➔ 4 millions d'années pour passer de 0 à 1 m/s (marche lente)

MICROSCOPE : 10 $^{-15}$ EP TEST through UFF



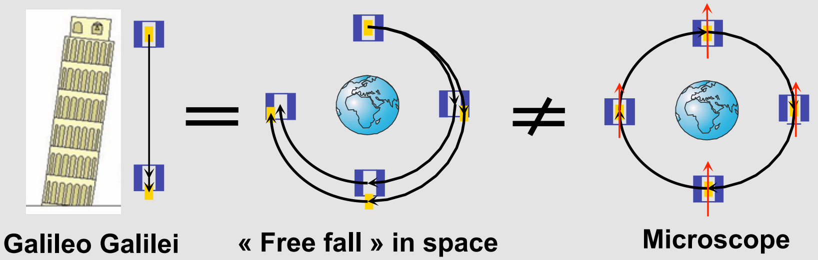
- Gravitational Source : the Earth
- Inertial Acceleration : Orbital Motion
- Control of 2 times 2 masses of different & identical composition

→ Along the same orbit (< 10^{-11}m),

→ With servo-controlled electrostatic pressures.

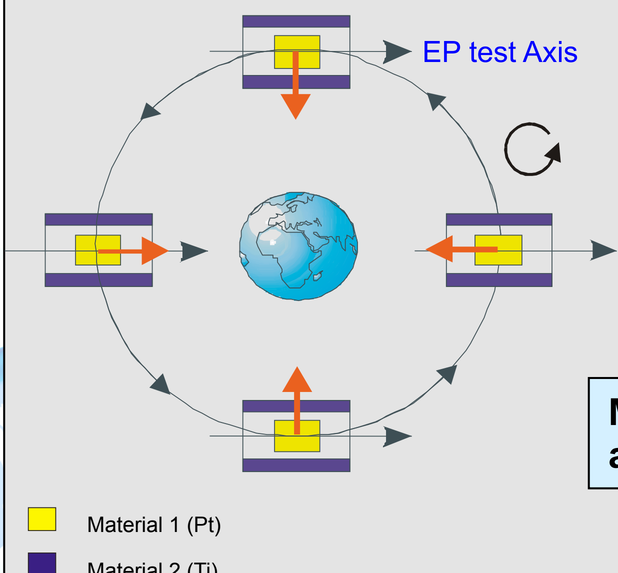
→ Observation of any dissymmetry along Earth Monopole direction

MICROSCOPE : 10 $^{-15}$ EP TEST through UFF

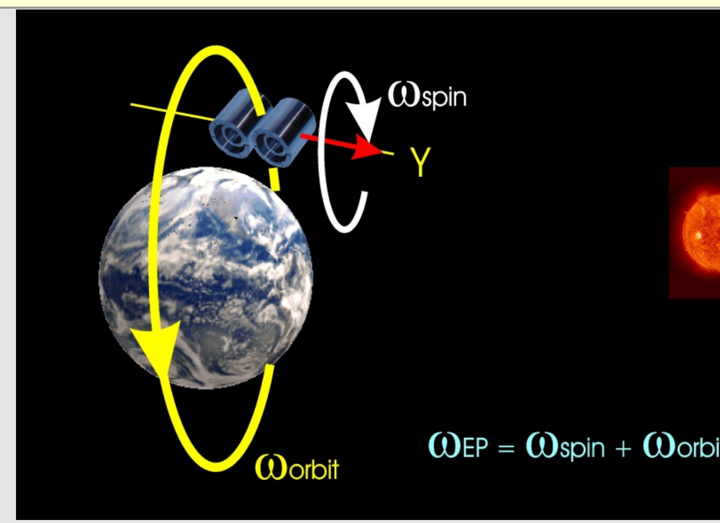


- Gravitational Source : the Earth
- Inertial Acceleration : Orbital Motion
- Control of 2 masses of different & identical composition
- → Along the same orbit (< 10^{-11}m),
- → With servo-controlled electrostatic pressures.
- → Observation of any dissymmetry along Earth Monopole direction

- Dedicated space instrument
- Mission duration : 2 years
- Test duration : series of 20 orbits ~ 1.2 × 10^5 s
- Signal to be observed at EP test phase & frequency
  - → rejection of stochastic and tone disturbing signals
- Spatial environment : reduced or controlled disturbances

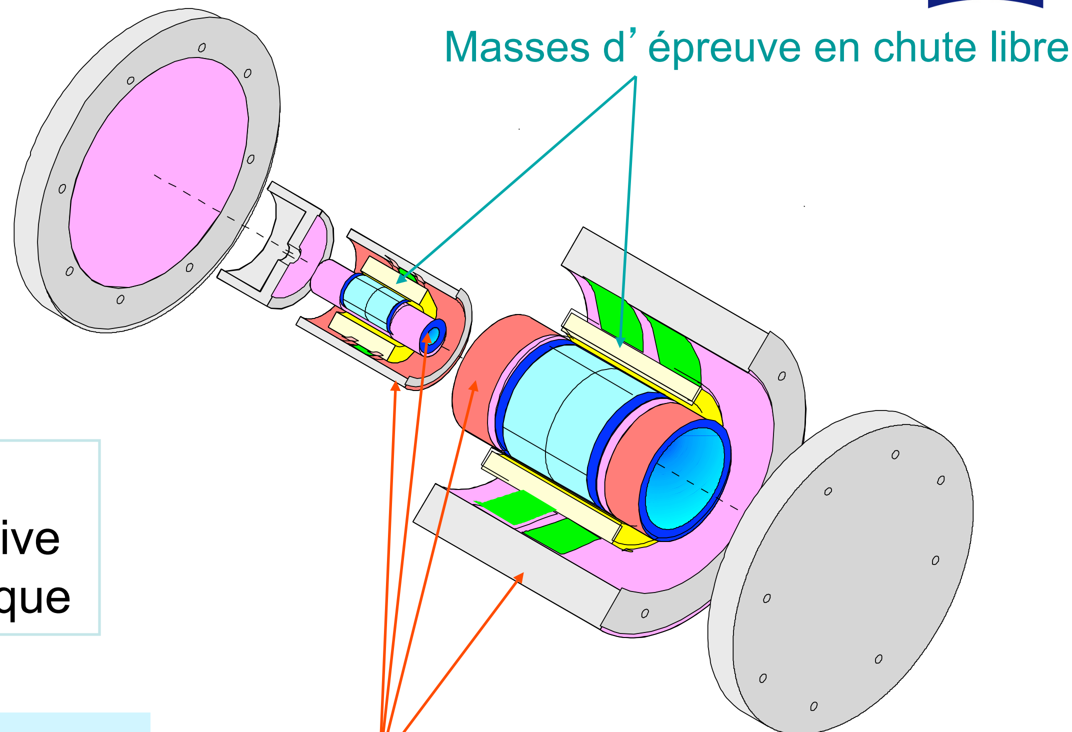


Mass material : Pt and Ti alloys



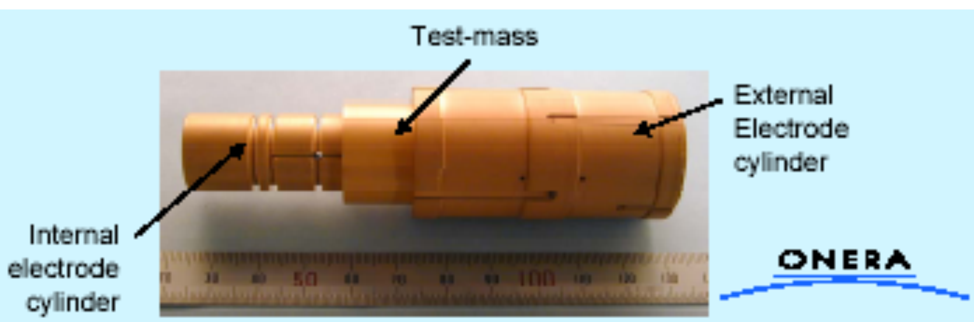
Les détecteurs

- Test-Masses (jaune)
- Sensitive axial electrodes (rouge)
- Spin control electrodes (vert)
- Levitation control electrodes (cyan)
- Electrostatic shield (rose)



Document ONERA

La position des masses (jaunes)
est déterminée par détection capacitive
et contrôlé par une force électrostatique



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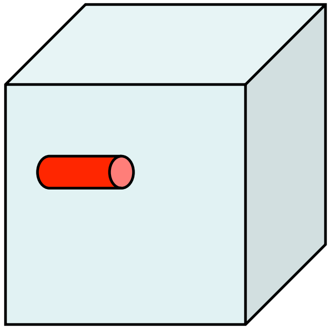
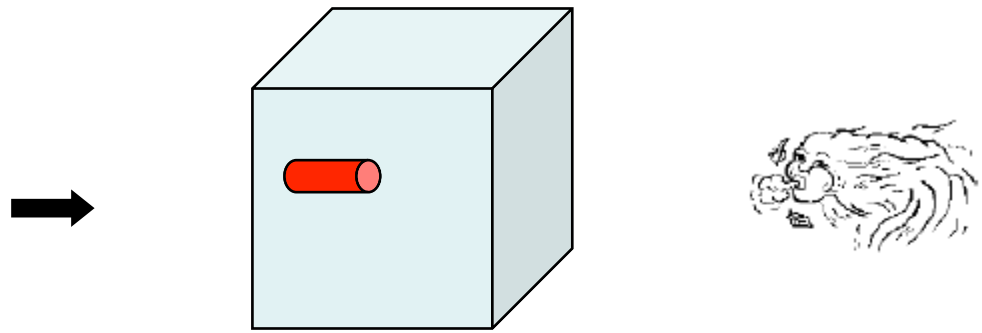
Le contrôle d'attitude et de traînée



Problème :
- Chaque masse mesure la différence d'accélération entre le satellite et la masse
- Elle mesure en particulier les accélérations non-gravitationnelles qui agissent sur la surface du satellite (freinage atmosphériques, pressions de radiation…)
- Ces accélérations valent plusieurs 10^{-8} ms^{-2}
- Pour mesurer mieux que 10^{-15}g = 8 10^{-15} ms^{-2}, il faut donc une dynamique et une prcision de mesure meilleur que 10^{7}

COMPLIQUE !

Le contrôle d'attitude et de traînée



Propulseurs à gaz froid (pas de combustion) :
- 8 propulseurs
- 6 réservoirs
- 16,5 kg de gaz

Les propulseurs servent également pour le contrôle d'attitude

Résidu de traînée < 10^{-12} ms^{-2}
Stabilité angulaire < 10^{-6} rad

} A la fréquence du test.

L'orbite

- Altitude : 700 km = compromis entre
  - Gravité importante, transmission des données, retombée en fin de vie ➔ altitude faible
  - Réduction du freinage ➔ altitude élevée
- Excentricité : 5 10^{-3} (la plus faible possible pour réduire l'impact du gradient de gravité)
- Inclinaison : 98° (héliosynchrone pour optimiser l'énergie et la stabilité thermique)

Differential acceleration between two test masses

$$2\overrightarrow{\gamma}^{(d)} = \Big([\mathbf{T}]\,(O_{12}) - [\mathbf{In}] \Big)\,\overrightarrow{O_1O_2}$$ *gradients: gravity and inertia*

$$+(\delta_2 - \delta_1)\,\overrightarrow{g}\,(O_{12})$$ *EP violation*

$$-2\,[\mathbf{\Omega}]\,\overset{\circ}{\overrightarrow{O_1O_2}} - \overset{\circ\circ}{\overrightarrow{O_1O_2}}$$ *relative motion of the test masses*

$$-2\overrightarrow{\gamma_p}^{(d)} - 2\,\overrightarrow{g}_S^{(d)}$$ *differential perturbations on the masses*

The potential EP violation signal is their but:

- We do not measure the difference of acceleration but we compute the difference of two measurements !
- Each of this measurement is affected by the sensor characteristics

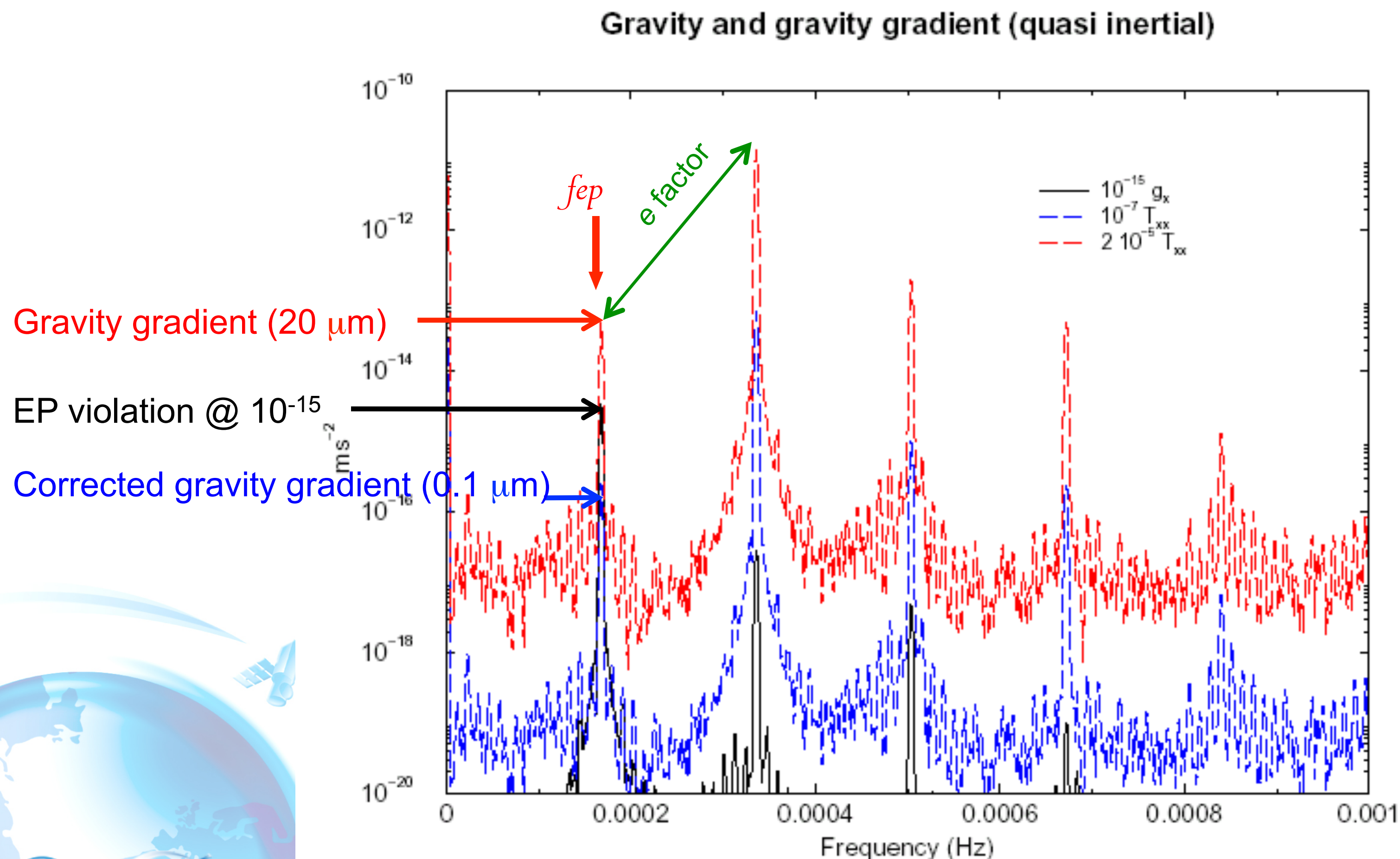
The differential measured acceleration

$$2\Gamma_x^{(d)} = 2B_x^{(d)}$$
$$+ \delta_x g_x + \delta_y g_y + \delta_z g_z$$
$$+ \Delta_x S_{xx} + \Delta_y S_{xy} + \Delta_z S_{xz} + (ac_{13}\Delta_y + ac_{12}\Delta_z) S_{yz} + ac_{12}\Delta_y S_{yy} + ac_{13}\Delta_z S_{zz}$$
$$+ (-ac_{13}\Delta_y + ac_{12}\Delta_z + 2nd_{11})\dot{\Omega}_x - (\Delta_z - 2ac_{13}\Delta_x + 2nd_{12})\dot{\Omega}_y + (\Delta_y - 2ac_{12}\Delta_x + 2nd_{13})\dot{\Omega}_z$$
$$+ 2\left(-ac_{13}\dot{\Delta}_y + ac_{12}\dot{\Delta}_z\right)\Omega_x - 2\left(\dot{\Delta}_z - 2ac_{13}\dot{\Delta}_x\right)\Omega_y + 2\left(\dot{\Delta}_y - 2ac_{12}\dot{\Delta}_x\right)\Omega_z$$
$$- mc_{11}\ddot{\Delta}_{x,inst} - mc_{12}\ddot{\Delta}_{y,inst} - mc_{13}\ddot{\Delta}_{z,inst}$$
$$+ 2\left(ad_{11}\Gamma_x^{(c)} + ad_{12}\Gamma_y^{(c)} + ad_{13}\Gamma_z^{(c)}\right)$$
$$+ K_{2xx}^{(1)}\left(\frac{\Gamma_x^{(1)} - {b_{0x}}^{(1)}}{{K_{1x}}^{(1)}}\right)^2 - K_{2xx}^{(2)}\left(\frac{\Gamma_x^{(2)} - {b_{0x}}^{(2)}}{{K_{1x}}^{(2)}}\right)^2$$

estimated by calibration
observed or/and computed
negligible at Fep

Target: 10^{-15} accuracy ⇔ 8 10^{-15} ms^{-2} in acceleration e = 0.005

Correction of the gravity gradient effects



Non white noise

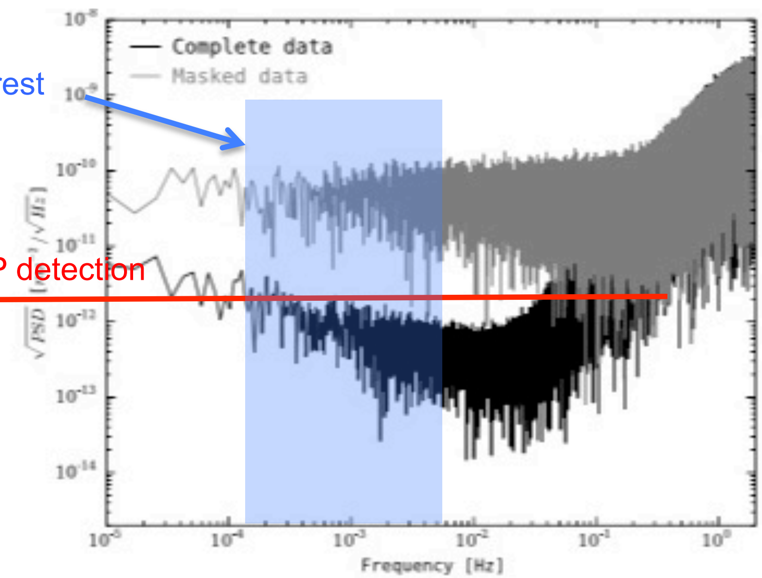


FIG. 1. Periodogram of original (black) and incomplete (grey) time series with 0.5 second data gaps randomly distributed in a 20 orbits session. The simulation is done for 260 random gaps per orbit.

Q. Baghi, G. Metris, J. Bergé, B. Christophe, P. Touboul, and M. Rodrigues. Phys. Rev. D, 91(062003), 2015.

➔ Data analysis

PSD reconstruite

REGRESSION ANALYSIS WITH MISSING DATA AND … PHYSICAL REVIEW D **91,** 062003 (2015)

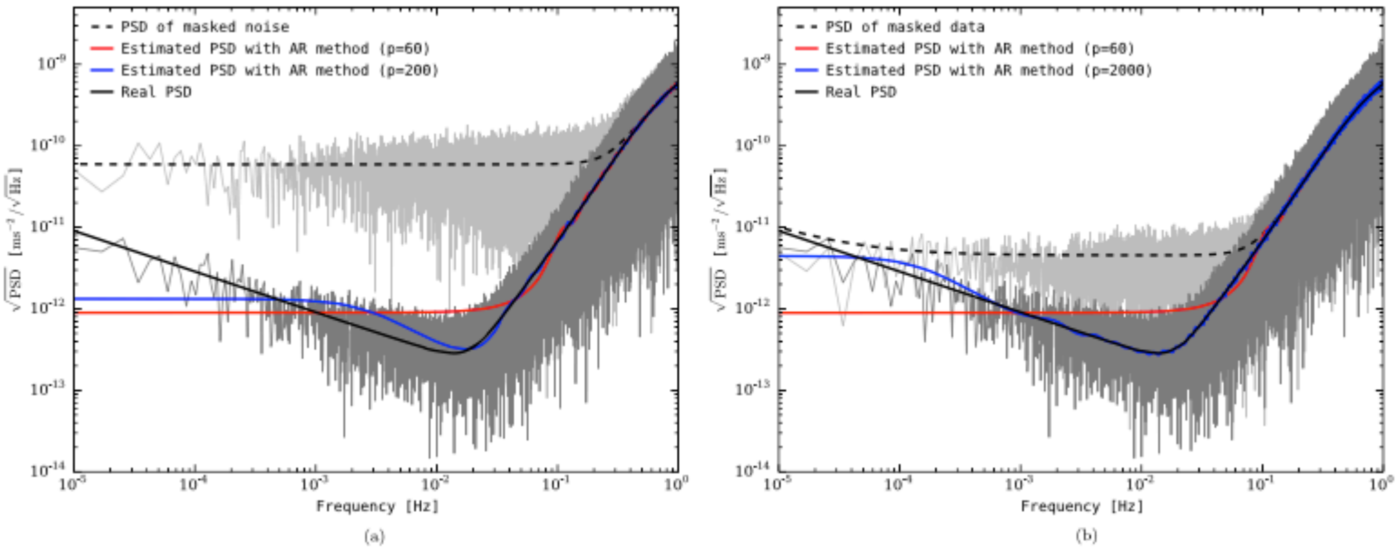
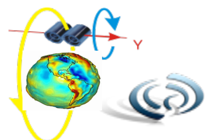


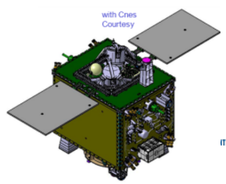
FIG. 4 (color online). PSD estimates of the noise in the presence of missing data. The black dashed curve is an estimate of the masked data PSD [obtained using Eq. (5)], the black solid curve is the actual noise PSD, and the red and blue curves are the PSD estimates of the AR model obtained with Burg's algorithm. The periodograms of the regression residuals are also plotted for the complete (dark grey) and masked (light grey) cases. (a) Tank crackles gaps. (b) Telemetry losses.

Present Scientific collaboration

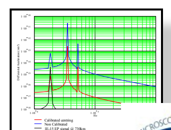


Observatoire de la Côte d’Azur

ONERA
THE FRENCH AEROSPACE LAB



cnes



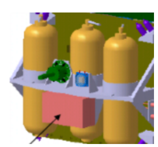
ZARM

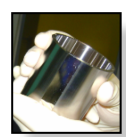
DLR

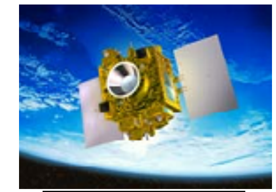
esa

PTB
Physikalisch-
Technische

Bundesanstalt







Scientific organization : Science Working Group

PI (ONERA) who is the Chairperson	Pierre Touboul	Mission Core Team
co-PI (OCA)	Gilles Metris	Mission Core Team
ZARM co-I for Space Physics	Claus Lämmerzhal	Mission Core Team
DLR co-I	Hansjoerg Dittus	Mission Core Team
General Relativity and Gravitation	Thibault Damour	Scientific Experts Per domain
Fundamental Interactions	Pierre Fayet	Scientific Experts Per domain
Interdisciplinary Physics	Serge Reynaud	Scientific Experts Per domain
Earth gravity field	Isabelle Panet	Scientific Experts Per domain
Aeronomy	Pieter Visser	Scientific Experts Per domain
European scientist representative of similar space missions	Tim Sumner	Scientific Experts Per domain
CNES Fundamental Physics coordinator	Sylvie Léon-Hirtz	Invited Permanent
CMS manager	Manuel Rodrigues	Invited Permanent
CNES project manager	Yves André	Invited when needed
Payload manager	Manuel Rodrigues	Invited when needed
CECT chairman	Alain Robert	Invited when needed

Towards a launch in spring 2016

Thank you for your attention

and welcome to the next Microscope Colloquium on November 16-17 in Palaiseau